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## PARAMETRIC STUDIES AND DESIGN RECOMMENDATIONS OF COLD-FORMED STEEL SECTIONS WITH WEB OPENINGS SUBJECTED TO WEB CRIPPLING

Ying LIAN<sup>a</sup>, Asraf UZZAMAN<sup>b</sup>, James B.P. LIM<sup>a,c</sup>, Gasser ABDELAL<sup>d</sup>, David NASH<sup>b</sup>,  
Ben YOUNG<sup>e</sup>

<sup>a</sup> School of Natural and Built Environment, David Keir Building, Queen's University, Belfast, BT9 5AG, UK  
Emails: ylian01@qub.ac.uk, james.lim@auckland.ac.nz

<sup>b</sup> Department of Mechanical and Aerospace Engineering, The University of Strathclyde, 75 Montrose Street,  
Glasgow G1 1XJ, UK  
Emails: asraf.uzzaman@strath.ac.uk, d.nash@strath.ac.uk

<sup>c</sup> Civil & Environmental Engineering, The University of Auckland, 20 Symonds Street, Auckland, New Zealand  
Email: james.lim@auckland.ac.nz

<sup>d</sup> Department of Mechanical and Aerospace Engineering, Queen's University, Belfast, BT9 5AH, UK  
Email: g.abdelal@qub.ac.uk

<sup>e</sup> Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong  
Email: young@hku.hk

**Keywords:** Cold-formed Steel; Web crippling; Web openings; Finite element analysis; Channel section; Reduction factor; Design recommendations.

**Abstract:** *A parametric study of cold-formed steel sections with web openings subjected to web crippling under interior-one-flange (IOF) and end-one-flange (EOF) loading conditions are undertaken, using finite element analysis, to investigate the effects of web holes and cross-sections sizes. The holes are located either centred beneath the bearing plate or with a horizontal clear distance to the near edge of the bearing plate. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the depth of the web, the ratio of the length of bearing plate to the flat depth of the web and the location of the holes as defined by the distance of the hole from the edge of the bearing plate divided by the flat depth of the web. In this paper, design recommendations in the form of web crippling strength reduction factor equations are proposed, which are conservative when compared with the experimental and finite element results.*

### 1 INTRODUCTION

Strength reduction factor equations have recently been proposed by Uzzaman et al. [1-4] for the web crippling strength of cold-formed steel channel sections with circular holes in the web under the end-two-flange (ETF) and interior-two-flange (ITF) loading conditions. This paper extends the work of Uzzaman et al. [1-4] to consider the interior-one-flange (IOF) and end-one-flange (EOF) loading condition for cold-formed steel channel sections with circular holes in the web.

In the literature, LaBoube *et al.* [5] have previously considered the case of a circular hole having a horizontal clear distance to the near edge of the bearing plates, but only for the case where the flanges are fastened to the bearing plates. The strength reduction factor equation proposed by LaBoube *et al.* [5] was subsequently adopted by the North American Specification (NAS) [6] for cold-formed steel sections. This strength reduction factor equation, however, was limited to thicknesses ranging from 0.83 mm to 1.42 mm. Other similar work described in the literature include that of Yu and Davis [7] who studied the case of both circular and square web openings located and centred beneath the bearing plates under the interior-one-flange loading condition, Sivakumaran and Zielonka [8] who considered the case of rectangular web openings located and centred beneath the bearing plates under the interior-one-flange loading condition, and Zhou and Young [9] who proposed strength reduction factor equations for aluminium alloy square sections with circular web openings located and centred beneath the bearing plates under the end-two-flange and interior-two-flange loading conditions. Recent research on web crippling of cold-formed steel channel sections, other than that by Uzzaman *et al.* [1-4], who again considered only the two-flange loading conditions, has not covered the case of holes.

Experimental and numerical investigations have been discussed in Lian *et al.* [10-13]. In this paper, non-linear finite element analyses (FEA) are used to conduct parametric studies to investigate the effect of circular web holes on the web crippling strength of lipped channel sections for the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions. The cases of both flanges fastened and unfastened to the support are considered. In both loading conditions, the holes were located centred beneath the load or reactions plate (Type 1 holes) and with an offset distance to the bearing plate (Type 2 holes). The general purpose finite element program ABAQUS [14] was used for the parametric study. Based on the test data found in Lian *et al.* [10-13] and the numerical results obtained from this study an extensive statistics analysis is performed. Design recommendations in the form of web crippling strength reduction factors are proposed for IOF and EOF loading conditions that are shown to be conservative to both the experimental and finite element results.

## 2 PARAMETRIC STUDY

The finite element model developed closely predicted the experimental ultimate loads and failure modes of the channel sections with and without circular web holes subjected to web crippling [10-13]. Using this model, parametric studies were carried out to study the effects of web holes and cross-section sizes on the web crippling strengths of channel sections subjected to web crippling under IOF and EOF loading conditions. The cases of both flange fastened and flange unfastened to the support were considered. The web holes were located at the mid-depth of the webs.

Zhou and Young [9] and LaBoube *et al.* [5] showed that the ratios  $a/h$ ,  $N/h$  and  $x/h$  are the primary parameters influencing the web crippling behaviour of the sections with web holes. The web crippling strength predicted was influenced primarily by the ratio of the hole depth to the flat portion of the web,  $a/h$ , the ratio of the bearing length to the flat portion of the web  $N/h$  and the location of the hole as defined by the distance of the hole from the edge of the bearing divided by the flat portion of the web,  $x/h$ . In order to determine the effect of  $a/h$  and  $N/h$  on the web crippling strength for Type 1 web holes and the effect of  $a/h$  and  $x/h$  on web crippling strength for Type 2 web holes, two separate parametric studies were carried out considering the web holes sizes, the cross-section sizes and location of the holes.

The specimens consisted of three different section sizes, having thicknesses ( $t$ ) ranging from 1.23 mm to 6.0 mm and web slenderness ( $h/t$ ) values ranging from 111.7 to 157.8. The ratios of the diameter of the holes ( $a$ ) to the depth of the flat portion of the webs ( $h$ ) were 0.2, 0.4, 0.6 and 0.8. The ratios of the distance of the holes ( $x$ ) to the depth of the flat portion of the web ( $h$ ) were 0.2, 0.4 and 0.6. For each series of specimens, the web crippling strengths of the sections without the web holes were obtained. Thus, the ratio of the web crippling strengths for sections with the web holes divided by the sections without the web holes, which is the strength reduction factor ( $R$ ), was used to quantify the degrading influence of the web holes on the web crippling strengths.

## 2.1 Effects of $a/h$ and $N/h$ on web crippling strength reduction for Type 1 web holes

A total of 193 specimens for IOF and 182 specimens for EOF loading conditions were analysed in the parametric study to investigate the effects of the ratio  $a/h$  and  $N/h$ .

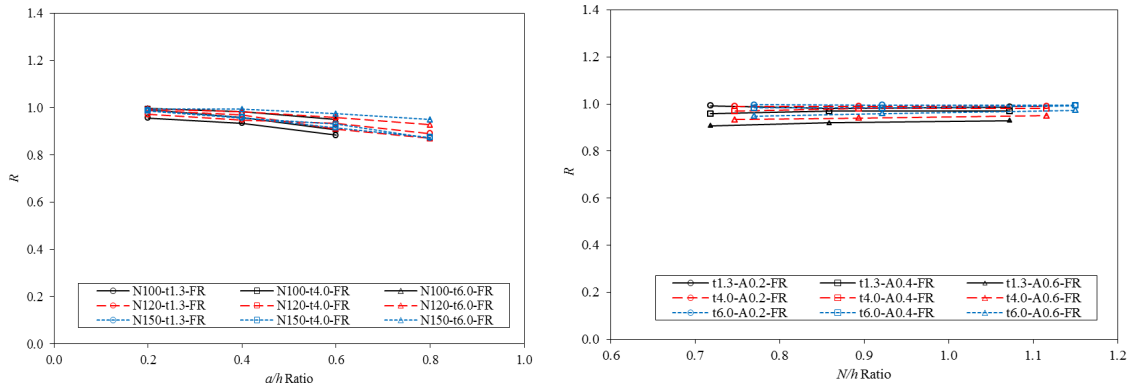


Figure 1: Variation in reduction factors with  $a/h$  and  $N/h$  for under IOF loading condition

The cross-section dimensions as well as the web crippling strengths ( $P_{FEA}$ ) per web predicted from the FEA are summarised in Lian et al. [10-13] for flanges unfastened and fastened condition, respectively. The effects of  $a/h$  and  $N/h$  ratio on the web crippling strength on the reduction factor for flanges unfastened and fastened condition are shown in Fig.3 and Fig.4 for the C142 specimen. It can be seen that the reduction in strength is not sensitive to the ratio  $N/h$ . Again the 6 mm thick sections have the smallest reduction in strength (or the highest strength reduction factor); also, as the parameter  $a/h$  increases the reduction in strength decreases and that the reduction in strength increases as the section becomes thinner.

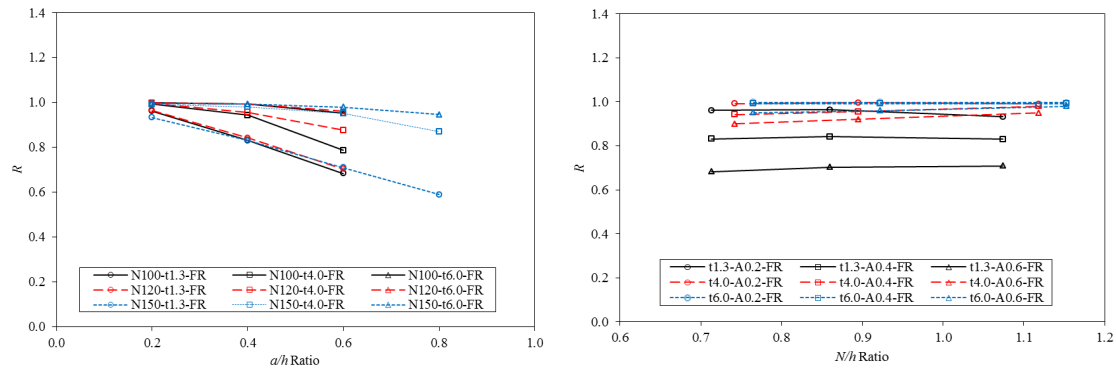


Figure 2: Variation in reduction factors with  $a/h$  and  $N/h$  for under EOF loading condition

## 2.2 Effects of $a/h$ and $N/h$ on web crippling strength reduction for Type 2 web holes

A total of 512 specimens for IOF and 456 specimens for EOF loading conditions were analysed in the parametric study to investigate the effect of the ratio  $a/h$  and  $x/h$ . The cross-section dimensions as well as the web crippling strengths per web predicted from the FEA are summarised in Lian *et al.* [10-13] for flanges unfastened and fastened condition, respectively. The effects of  $a/h$  and  $x/h$  ratio on the web crippling strength on the reduction factor are shown in figure 1 and figure 2 for the C142 specimen, respectively. It is seen from these graphs that the parameter  $a/h$  and  $x/h$  noticeably affects the web crippling strength and the reduction factor. The failure load decreases as the size of the web holes increases and the failure load increases as the distance of the web holes increases.

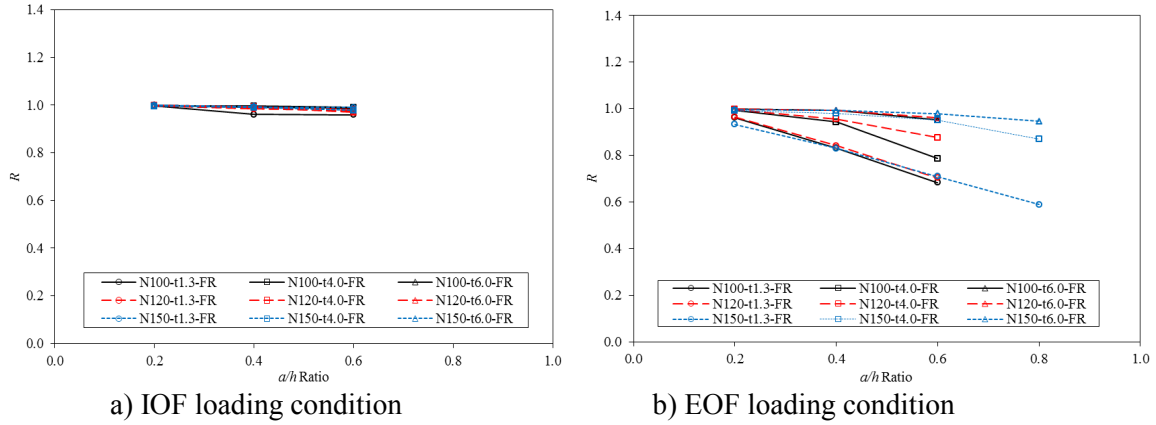


Figure 3: Variation in reduction factors with  $a/h$  ratio

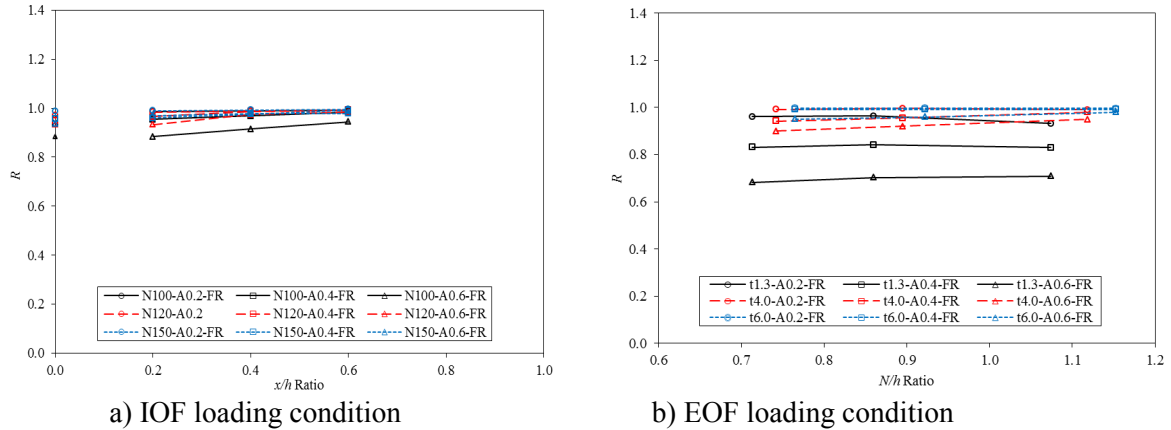


Figure 4: Variation in reduction factors with  $x/h$  ratio

## 3 RELIABILITY ANALYSIS

The reliability of the cold-formed steel section design rules is evaluated using reliability analysis. The reliability index ( $\beta$ ) is a relative measure of the safety of the design. A target reliability index of 2.5 for cold-formed steel structural members is recommended as a lower limit in the NAS Specification [6]. The design rules are considered to be reliable if the reliability index is greater than or equal to 2.5. The load combination of  $1.2DL + 1.6LL$  as specified in the American Society of Civil Engineers Standard [17] was used in the reliability analysis, where DL is the dead load and LL is the live load. The statistical parameters are obtained from Table F1 of the NAS Specification [6] for compression members, where  $M_m = 1.10$ ,  $F_m =$

1.00,  $V_M = 0.10$ , and  $V_F = 0.05$ , which are the mean values and coefficients of variation for material properties and fabrication factors.

In calculating the reliability index, the correction factor in the NAS Specification was used. Reliability analysis is detailed in the NAS Specification [6]. In the reliability analysis, a constant resistance factor ( $\phi$ ) of 0.85 was used. It is shown that the reliability index ( $\beta$ ) is greater than the target value of 2.5 as shown in Tables 1 and Table 2.

#### 4 COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS WITH CURRENT DESIGN STRENGTHS FOR COLD-FORMED STEEL SECTIONS WITHOUT WEB HOLES

As mentioned earlier, the current cold-formed design standards [6, 15, 16] do not provide design rules for cold-formed steel sections with web holes subjected to web crippling under IOF and EOF loading conditions. The web crippling strength predicted from test and FEA results were compared with the web crippling strength obtained from design codes. The comparison of the web crippling test strengths and the numerical results with design strength for EOF and IOF loading conditions are shown in Lian et al. [10-13]. It is noted that for the unfastened case agreement is very good, however, for the fastened case, the comparison is less reliable due to the post buckling strength effect not being fully considered in the design codes.

#### 5 PROPOSED STRENGTH REDUCTION FACTORS

##### 5.1 Proposed strength reduction factor IOF loading condition

Based on both the experimental and numerical results reported by Lian et al. [10-13], four strength reduction factor ( $R_p$ ) are proposed using bivariate linear regression analysis for the IOF loading condition.

For centred hole:

For the case where the flange is unfastened to the bearing plate,

$$R_p = 0.98 - 0.26\left(\frac{a}{h}\right) + 0.06\left(\frac{N}{h}\right) \leq 1 \quad (1)$$

For the case where the flange is fastened to the bearing plate,

$$R_p = 0.95 - 0.06\left(\frac{a}{h}\right) + 0.01\left(\frac{N}{h}\right) \leq 1 \quad (2)$$

For offset hole:

For the case where the flange is unfastened to the bearing plate,

$$R_p = 0.99 - 0.26\left(\frac{a}{h}\right) + 0.11\left(\frac{x}{h}\right) \leq 1 \quad (3)$$

For the case where the flange is fastened to the bearing plate,

$$R_p = 0.99 - 0.14\left(\frac{a}{h}\right) + 0.07\left(\frac{x}{h}\right) \leq 1 \quad (4)$$

The limits for the reduction factor equations (3), (4), (5) and (6) are  $h/t \leq 157.8$ ,  $N/t \leq 120.97$ ,  $N/h \leq 1.15$ ,  $a/h \leq 0.8$ , and  $\theta = 90^\circ$ .

## 5.2 Proposed strength reduction factor EOF loading condition

Based on both the experimental and numerical results reported by Lian *et al.* [10-13], four strength reduction factor ( $R_p$ ) are proposed using bivariate linear regression analysis for the EOF loading condition.

For centred hole:

For the case where the flanges are unfastened to the bearing plates,

$$R_p = 0.96 - 0.34\left(\frac{a}{h}\right) + 0.09\left(\frac{N}{h}\right) \leq 1 \quad (5)$$

For the case where the flanges are fastened to the bearing plates,

$$R_p = 0.93 - 0.41\left(\frac{a}{h}\right) + 0.16\left(\frac{N}{h}\right) \leq 1 \quad (6)$$

For offset hole:

For the case where the flanges are unfastened to the bearing plates,

$$R_p = 0.97 - 0.26\left(\frac{a}{h}\right) + 0.14\left(\frac{x}{h}\right) \leq 1 \quad (7)$$

For the case where the flanges are fastened to the bearing plates,

$$R_p = 0.97 - 0.14\left(\frac{a}{h}\right) + 0.07\left(\frac{x}{h}\right) \leq 1 \quad (8)$$

The limits for the reduction factor in equations (2), (3), (4) and (5) are  $h/t \leq 157.8$ ,  $N/t \leq 120.97$ ,  $N/h \leq 1.15$ ,  $a/h \leq 0.8$ , and  $\theta = 90^\circ$ .

## 6 COMPARISON OF THE EXPERIMENT AND NUMERICAL RESULTS WITH THE PROPOSED REDUCTION FACTOR

For IOF loading condition, the values of the strength reduction factor ( $R$ ) obtained from the experimental and the numerical results are compared with the values of the proposed strength reduction factor ( $R_p$ ) calculated using Eqs. (1), (2), (3) and (4). Table 1 summarizes a statistical analysis to define the accuracy of the proposed design equations. The values of the proposed reduction factor are generally conservative and agree well with the experimental and the numerical results for IOF loading conditions. As can be seen, the proposed reduction factors are generally conservative and agree with the experimental and the numerical results for all cases. The mean value of the web crippling reduction factor ratio are 1.01, 1.01, 1.00 and 1.00 with corresponding values of COV of 0.05, 0.06, 0.04 and 0.03, and reliability index ( $\beta$ ) of 2.85, 2.81, 2.84 and 2.85 for the flanges are unfastened and fastened conditions with both types of web holes. Thus, the proposed strength reduction factor equations are able to predict the influence of the web holes on the web crippling strengths of channel sections for the IOF loading condition.

**Table 1:** Statistical analysis for the comparison of the strength reduction factor for IOF loading condition

Statistical parameters	$R$ (Test & FEA) / Eq. (1)	$R$ (Test & FEA) / Eq. (2)	$R$ (Test & FEA) / Eq. (3)	$R$ (Test & FEA) / Eq. (4)
	Unfastened	Fastened	Unfastened	Fastened
	Type 1 holes	Type 2 holes	Type 1 holes	Type 2 holes
Mean, $P_m$	1.01	1.01	1.00	1.00

Coefficient of variation, $V_p$	0.05	0.06	0.04	0.03
Reliability index, $\beta$	2.85	2.81	2.84	2.85
Resistance factor, $\phi$	0.85	0.85	0.85	0.85

For EOF loading condition, the values of the strength reduction factor ( $R$ ) obtained from the experimental and the numerical results are compared with the values of the proposed strength reduction factor ( $R_p$ ) calculated using equations. (5), (6), (7) and (8).

**Table 2:** Statistical analysis for the comparison of the strength reduction factor for EOF loading condition

Statistical parameters	$R$ (Test & FEA) / Eq. (5)	$R$ (Test & FEA) / Eq. (6)	$R$ (Test & FEA) / Eq. (7)	$R$ (Test & FEA) / Eq. (8)
	Unfastened	Fastened	Unfastened	Fastened
	Type 1 holes	Type 2 holes	Type 1 holes	Type 2 holes
Mean, $P_m$	1.00	1.00	1.00	1.01
Coefficient of variation, $V_p$	0.091	0.092	0.042	0.029
Reliability index, $\beta$	2.69	2.69	2.86	2.91
Resistance factor, $\phi$	0.85	0.85	0.85	0.85

Table 2 summarizes a statistical analysis to define the accuracy of the proposed design equations. The values of the proposed reduction factor are generally conservative and agree well with the experimental and the numerical results for EOF loading conditions. As can be seen, the proposed reduction factors are generally conservative and agree with the experiment and the numerical results for both load cases. The mean value of the web crippling reduction factor ratio are 1.00, 1.00, 1.00 and 1.01 with the corresponding COV of 0.091, 0.092, 0.042 and 0.029, and reliability index ( $\beta$ ) of 2.69, 2.69, 2.86 and 2.91 for the flanges are unfastened and fastened conditions with both types of web holes, respectively. Thus, the proposed strength reduction factor equations are able to predict the influence of the web holes on the web crippling strengths of channel sections for the EOF loading condition.

## 7 CONCLUSIONS

The main conclusions are:

1. A parametric study of lipped channel sections with circular web holes subjected to web crippling has been presented. The web holes are located at the mid-depth of the webs and centred beneath the bearing plates or centred above the bearing plates or with a horizontal clear distance to the near edge of the bearing plate.
2. A non-linear finite element model was used in the parametric study, which has been verified against experiment results. Evaluation of the experimental and the numerical results shows that the ratios  $a/h$ ,  $N/h$  and  $x/h$  are the primary parameters influencing the web crippling behaviour of the sections with web holes. In order to determine the effect



of the ratios  $a/h$ ,  $N/h$  and  $x/h$  on the web crippling strength, parametric studies were carried out considering the web holes, the cross-section sizes and the different bearing plate lengths.

3. Based on the available data obtained from the experimental and numerical investigations, web crippling strength reduction factor equations were proposed for the IOF and EOF loading conditions for the cases of both flanges unfastened and fastened to the support.
4. Reliability analysis was performed to evaluate the reliability of the proposed strength reduction factors. It was shown that the proposed strength reduction factors are generally conservative and agree well with the experimental and the numerical results.

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## NOTATION

$A$	Web holes ratio
$a$	Diameter of circular web holes
COV	Coefficient of variation
$DL$	Dead load
FEA	Finite element analysis
$F_m$	Mean value of fabrication factor
$h$	Depth of the flat portion of web
$LL$	Live load
$M_m$	Mean value of material factor
$N$	Length of the bearing plate
$P_m$	Mean value of tested-to-predicted load ratio
$R$	Reduction factor
$R_P$	Proposed reduction factor
$V_F$	Coefficient of variation of fabrication factor
$V_M$	Coefficient of variation of material factor
$V_P$	Coefficient of variation of tested-to-predicted load ratio
$x$	Horizontal clear distance of the web holes to the near edge of the bearing plate
$\beta$	Reliability index
$\phi$	Resistance factor

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